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Current-voltage characteristic and electroluminescence of UV LEDs 365 nm at liquid nitrogen temperature

Vitaly VELESCHUK[1*], Alexander VLASENKO[1], Zoya VLASENKO[1], Ihor PETRENKO[2], Yevhen MALYI[2], Vladimir BORSHCH[3], Olena BORSHCH[3], Alexander SHEFER[3]

[1] V.Ye. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Nauki Avenue 41, 03028 Kyiv, Ukraine

[2] Institute for Nuclear Research, National Academy of Sciences of Ukraine, Nauki Avenue 47, 03028 Kyiv, Ukraine

[3] Poltava National Technical Yuri Kondratyuk University, Pershotravnevyi Avenue 24, 36011 Poltava, Ukraine

[*] Corresponding author: vvvit@ukr.net

For InGaN/AlGaN/GaN ultraviolet (λ = 365 nm) light emitting diodes, the S-shaped current-voltage characteristic was observed at liquid nitrogen temperature due to the transition from single injection (electrons) to double (electrons and holes) injection. Initially only electron injection into the active region takes place and as the current is increased, the injection of holes starts. It has been found that at the voltage of the minimum of the negative differential resistance region, oscillations of the current, accompanied by increasing electroluminescence intensity arise, and the repetition rate of the oscillations increases with the direct current rise. The intensity of the main ultraviolet and yellow electroluminescence bands sharply increases with increasing current at negative differential resistance region due to the rise of holes injection.

Keywords: S-shaped current-voltage characteristic, UV LED.

1. Introduction

The light emitting diodes (LEDs) of the ultraviolet (UV) radiation with a maximum wavelength of 365 nm have a wide range of applications. This is, for example, polymerization, fluorescence microscopy in medicine and biology, luminescence spectroscopy, *etc*. [1–6]. However, the InGaN/AlGaN/GaN heterostructures of the ultraviolet LEDs have many disadvantages: undesirable tunneling effects that cause significant leakage current, yellow electroluminescence (EL) of defects [2, 3] and photoluminescence (PL) excitation in the LEDs structures from own UV radiation. Visible EL and PL from

UV LEDs cause problems by aliasing with photoluminescence of materials and structures that emit in the same spectral range [3]. These problems are caused by the presence of a shallow and deep levels of various defects and impurities in the depletion layer of the wide-band heterostructure and, as a result, they reduce the external quantum efficiency of the UV LEDs [1–4].

It is obvious that the processes of current flow and deep level (DL) recombination of defects and doping impurities in the UV LEDs strongly depend on the temperature in the range of 77–300 K. The DL affects the electrical and luminescent properties of UV LEDs at low temperatures, but the *I-V* characteristics and the spectra of the visible, parasitic luminescence of UV LEDs at $T = 77$ K have not been well-studied. Taking into account that DL partially causes the losses of UV radiation (up to 20% [3]) and low external quantum efficiency, the study of effects in the UV LEDs associated with deep levels is important.

In this paper we investigate *I-V* characteristics and luminescent properties of UV LEDs ($\lambda = 365$ nm) at low temperatures.

2. Experiment

The industrial InGaN/AlGaN/GaN LEDs, prepared by the MOCVD method on the sapphire substrate were investigated. LEDs emitting peak is at $\lambda_{peak} = 365$–370 nm, nominal current $I_{nom} = 20$ mA, electric power $P_{el} = 0.1$ W, the area of structure is 360×360 μm^2. Some information of such UV LED structure is described in [1, 5]; n-layers Si-doped, p-layers Mg-doped, $In_{0.02}Ga_{0.98}N$ quantum well thickness about 30 Å. The EL spectra were measured using the spectroradiometer HAAS-2000 (Everfine) and UV-spectrometer. The *I-V* characteristics in the mode of direct current and EL spectra were measured in the special cryostat at liquid nitrogen temperature.

3. Results

In Fig. 1, curve 1 presents the S-shaped *I-V* characteristic of the UV LED at $T = 77$ K with a negative differential resistance (NDR) region. It is known that S-shaped *I-V* characteristics are inherent to GaP green/red LEDs [7, 8] and InGaN/GaN blue LEDs [8, 9], NDR was observed in UV LEDs [2] and in InGaN/GaN lasers (407 nm) [10]. The breakdown voltage $U_B = 6.2$ V at $I = 3$–4 mA (Fig. 1, curve 1), the region of the negative differential resistance ends with a current $I = 36$–40 mA. The voltage of the beginning and the end of the NDR region depends on the temperature (Fig. 1, curve 2) and disappears at approximately $T = 187$ K (–86 °C) (Fig. 1, curve 3).

Note that under these voltages and at liquid nitrogen temperature, *I-V* and EL degradation for 5 cycles of measurements was not observed.

In the NDR region, which is shown by the arrow in Fig. 1, curves 1 and 2, oscillations of current and, respectively, EL intensity were observed, which are shown in Fig. 2. In Fig. 1, curve 1 indicates the triangle points to which Figs. 2**a**, 2**b**, 2**c** corre-

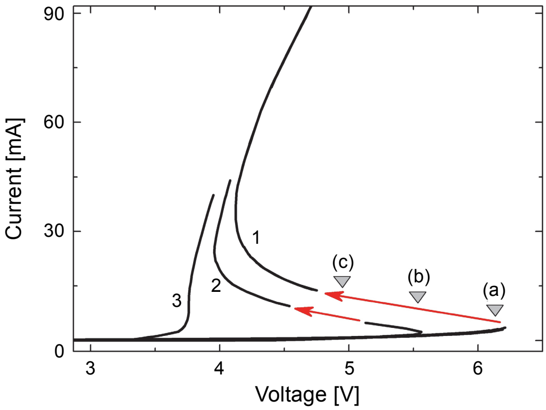

Fig. 1. The *I-V* characteristics of the UV LED 365 nm at $T = 77$ K (1), $T = 100$ K (2) and $T = 187$ K (3).

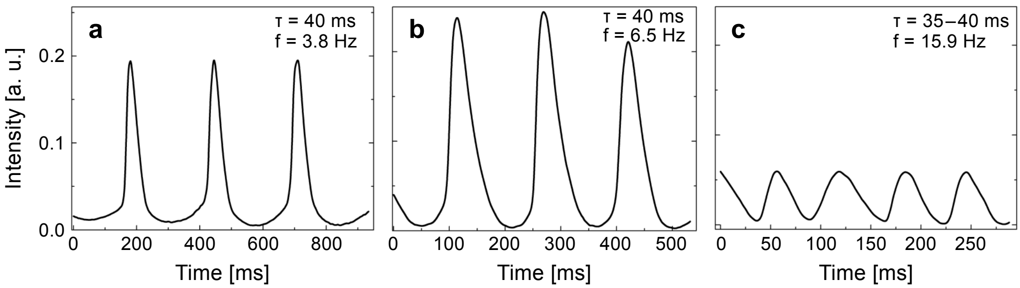

Fig. 2. Electroluminescence pulses in the NDR region (as shown in Fig. 1, curve 1) at various direct currents: 4 mA (**a**), 7 mA (**b**), and 10 mA (**c**).

spond respectively. It is seen that in this region of the NDR there is a generation of the EL pulses with a full width at half maximum $\tau = 40$ ms, and when the magnitude of the direct current increases from 3 to 12 mA, the repetition rate of pulses increases continuously from $f = 2$ to 17 Hz, and some of their intermediate amplitude changes as shown in Fig. 2. These EL pulses were registered by the Si p-i-n photodiodes with a rise/fall time of 20 ns and spectral range 350–1100 nm. At temperature rises this region of instability, which is shown by an arrow, diminished and disappeared at approximately $T = 110$ K.

The electroluminescence spectra of the UV LEDs contain the main UV band (Fig. 3**a**) and the well-known yellow band from $\lambda = 490$ nm to $\lambda = 700$ nm (Fig. 3**b**) related to the deep levels of defects [2, 3]. It was found that at $T = 77$ K the EL yellow band was absent (Fig. 3**b**, spectrum 1), then appears at a current of 2.8 mA (spectrum 2), and further on the NDR region its intensity sharply increases with rise of current (spectrum 3). The intensity of the main UV band also increases with current at $T = 77$ K, and extension of the spectra 1 and 2 (Fig. 3**a**) in the region of 380–420 nm is observed, which corresponds, probably, to electroluminescence at shallow levels in the quantum well.

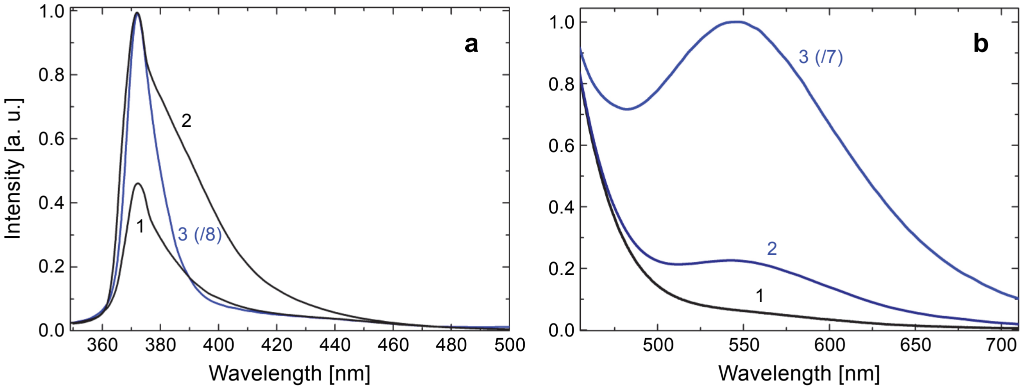

Fig. 3. Electroluminescence spectra of the UV LED 365 nm at currents 1 mA (1), 2.8 mA (2), 30 mA (3). UV band (**a**), yellow band (**b**); $T = 77$ K.

On the dependence of EL intensity on current for UV band at 77 K (Fig. 4, curve 1) two regions are observed – one is linear, which is saturated fully at current of 40 mA, that corresponds to the end of the NDR region. The second region has a monotonous decrease of intensity from 40 to 85 mA, while the *I*-*V* characteristic is almost linear. At the same time, the yellow band has some different dependence on current (Fig. 4, curve 2). There is practically linear dependence on current up to 40 mA, which corresponds to the end of NDR region and the region with another inclination after 40 mA, similar to the logarithmic dependence. So, after 40 mA the EL intensity dependence on current for UV and yellow bands is significantly different. In general, with the increase of the direct current at the NDR region a sharp increase of the EL intensity of the two bands is observed, and after the end of NDR region ($I = 40$ mA, $U = 4.13$ V), the intensity of the integrated EL increases weakly, despite the further significant in-

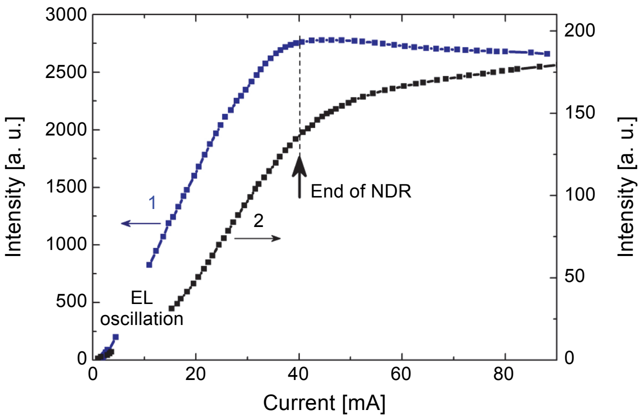

Fig. 4. Electroluminescence intensity dependence on current for UV (1) and yellow band (2) of the UV LED 365 nm at $T = 77$ K.

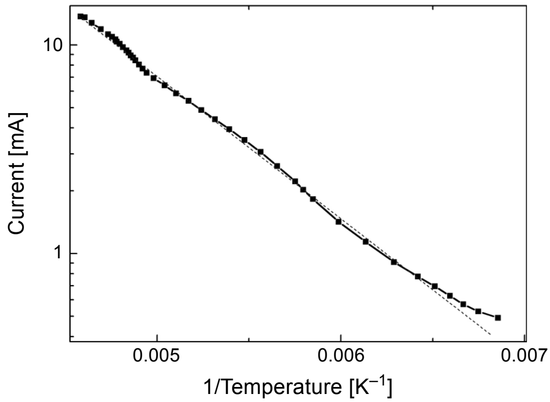

Fig. 5. Current dependence on temperature at a fixed voltage $U = 3.7$ V for UV LED.

crease of the current on the *I-V* dependence (Fig. 1). Such behavior of the two bands indicates to intensive recombination of the injected holes and electrons at the deep levels in the depletion layer of the LED structure.

It was found that in a certain temperature range at voltages lower than breakdown voltage the current I dependence on temperature T in the coordinates $\ln(I)-1/T$ has a pronounced linearity (Fig. 5). This fact allows us to determine the ionization energy of the deep levels responsible for S-shaped *I-V* characteristic. Indeed, according to the Ashley–Milnes theory, direct current at voltages lower than breakdown voltage is directly proportional to the concentration of thermally induced holes [11, 12]. The slope of the curve in Fig. 5 corresponds to the ionization energy of a deep level of 160 ± 20 meV.

4. Discussion

As for GaP LEDs, the UV LEDs heterostructure can be considered as the p-i-n junction, where i-region is the InGaN quantum well. S-shaped *I-V* characteristic at $T = 77$ K appears due to the presence of a deep level in the i-region (quantum well) and can be described by the Ashley–Milnes theory [11, 12].

Figure 6 presents band diagram of the UV LED structure and the processes of electrons and holes migration and recombination for three regions of S-shaped *I-V* characteristic: before breakdown voltage U_B (**a**), for NDR region (**b**) and after the end of NDR region (**c**). Also yellow and UV radiation at recombination are shown.

Deep-lying acceptors (recombination centers) are partially occupied by the electrons. The energy level of the recombination centers in the bandgap should be sufficiently deep so that the small number of thermally induced holes becomes negligible compared to much larger density of injected holes at low temperatures. At current injection the DL in the i-region plays the role of recombination centers of electrons and holes. The negative differential resistance at $T = 77$ K appears because the capture -cross section for holes σ_p is considerably larger than the capture-cross section for elec-

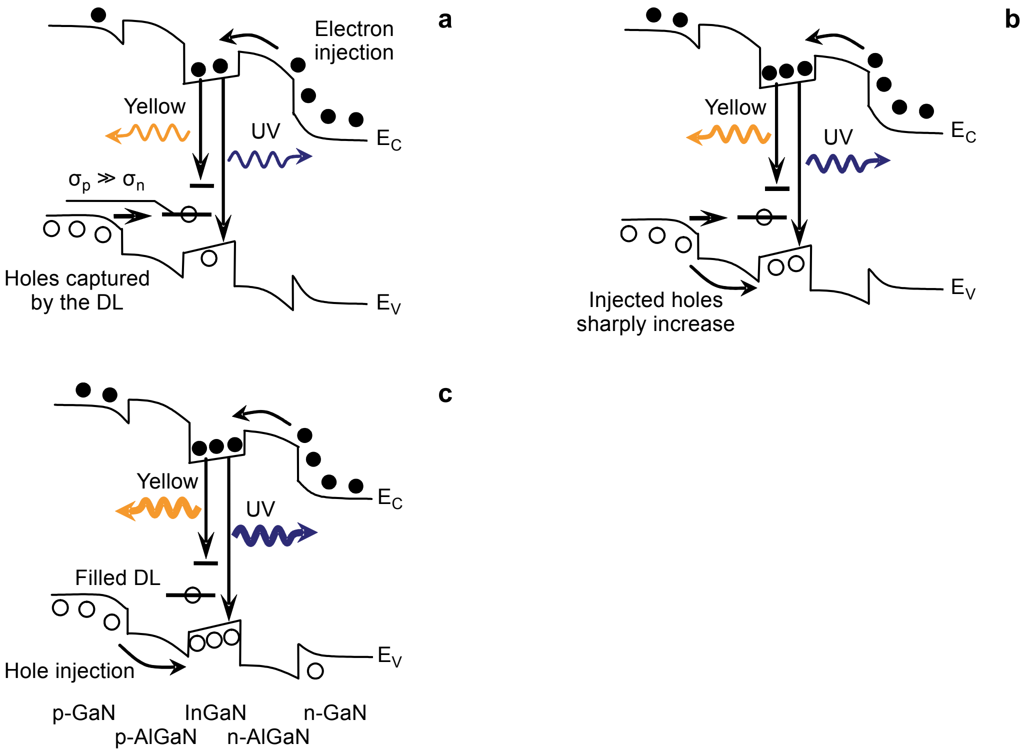

Fig. 6. Band diagram and the processes of electrons and holes migration and recombination along UV LED structure for three regions of S-shaped *I-V* characteristic. Before breakdown voltage (**a**), NDR region (**b**), and after NDR region (**c**).

trons σ_n of the recombination centers (Fig. 6**a**). The breakdown voltage and NDR is characterized by a large increase of injected holes (Fig. 6**b**). The breakdown voltage

$$U_B = L^2 \sqrt{\frac{e\sigma_p \upsilon_{tp}}{4\pi\varepsilon\mu_p}} N_{th}$$

corresponds to a holes transit time $\tau = L/\mu_p E$ across i-region which is approximately equal to the holes lifetime [11]. Here N_{th} is the density of recombination centers (hole traps), L is the i-region thickness (InGaN quantum well), υ_{tp} is the hole thermal velocity, μ_p is the hole mobility, and ε is the permittivity.

Once the holes become successful in making the transit without recombining on the DL, the *I-V* characteristic changes drastically because the conduction process switches from a single-injection mechanism (electrons) to a double-injection mechanism (electrons and holes). In other words, before breakdown voltage initially only electron injection into the active region takes place and as the current is increased, the injection of holes starts after breakdown voltage U_B. After the end of the NDR region all hole traps (DL) are filled (Fig. 6**c**).

At the beginning of the NDR region conduction process is strongly influenced by the deep levels and also sharp increase in lifetime of injected carriers associated with filling of these deep levels. At the end of the NDR region the heterostructure has a minimal resistance.

NDR-regime in semiconductor structures with S-shaped (*i.e.* current controlled) *I*-*V* characteristic leads to a number of effects, including the generation of current pulses due to instability, the reasons and mechanisms of such instability may be different. Such voltage oscillations were observed for GaP LEDs at T = 77 K in the NDR-regime [7]. Let us discuss the possible mechanism for the appearance of the *I*, *U* instability and, accordingly, the observed electroluminescence intensity oscillations at the beginning of the NDR region (Fig. 2).

The injection increase is limited by the recombination and space charge in depletion layer. Also in the NDR region the current increase is accompanied by a contrary voltage decrease. The holes transition is limited by the recombination processes – both on the deep levels (traps) and band-to-band. At some direct current there is a partial filling of the DL by holes and therefore an increase of holes lifetime. At this moment injected holes can transit through the structure at slightly lower voltages, and there is an intense band-to-band recombination of injected holes and electrons. This band-to-band recombination on the contrary reduces the holes lifetime; also at voltage decrease in the NDR region the depletion layer width increases and the hole current decreases, respectively.

Deep levels again capture holes effectively. So, the holes lifetime is variable on time at direct current. EL oscillations at the current increasing (increase of the injection) are stopped when the number of injected holes is much greater than the number of recombination levels, *i.e.* when all hole traps (DL) are filled. With temperature increase the oscillation region disappears due to the increase of the density of thermally induced holes, as well as with the further increase of temperature the NDR region also disappears. It was found that at direct current increase the repetition rate of pulses of the EL intensity increases (Fig. 2), which indicates the possibility of the above described mechanism.

In the depletion layer of the UV LEDs many shallow and deep levels are observed, some of which are related with yellow EL and probably with S-shaped *I*-*V* curves. For example in [4] for the UV LEDs structures the 26–28 meV traps related to oxygen donors and 75–85 meV traps related to nitrogen vacancies were observed. The Si donors have ionisation energy of 14 meV. However, the identification of the DL with ionisation energy of 160 meV which is responsible for the appearance of the S- shaped *I*-*V* characteristic in our opinion requires further research. For example, in [11] for AlGaN/GaN p-i-n structures S- shaped *I*-*V* characteristic is related with Mg acceptor level.

It should be noted that in the paper [13] NDR is observed in the room-temperature *I*-*V* curves of InGaN/GaN multiple-quantum-well LEDs when the samples are pretreated with a negative voltage before sweeping. Variation of the charging state of the defect-induced hole traps is responsible for the anomalous *I-V* behaviors.

5. Conclusions

It is established that ultraviolet light emitting diodes (λ = 365 nm) at liquid nitrogen temperature have S-shaped *I-V* characteristic, and the negative differential resistance region arises due to the transition from single injection (electrons) to double injection (electrons and holes) and disappears at temperature about 187 K. Initially only electron injection into the active region takes place and as the current is increased, the injection of holes starts at breakdown voltage.

It has been found that at the voltage of the beginning of the NDR region oscillations of the current and increasing electroluminescence intensity arise, and the repetition rate of oscillations increases with direct current increasing. At the NDR region yellow electroluminescence intensity increases sharply due to injection and recombination of the holes at deep defect levels.

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